

LF/VLF and VHF lightning fast-stepped leader observations

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[1] This paper reports multiplatform observations of leader radiation preceding initial cloud-to-ground lightning return strokes by <6 ms. Specifically, we present multistation ground-based LF/VLF recordings of events with large-amplitude leader activity (comparable in amplitude to the return stroke amplitude). The events were selected for their coincidence with VHF observations by the FORTE satellite. Some FORTE VHF leader step observations have obvious direct and ground reflection components. For these steps, which temporally correspond to specific features in the ground LF/VLF field change records, we calculate a source height based on event satellite geometry. We determine source heights between 4.0 and 5.5 km. For FORTE records with multiple reflected events we calculate vertical leader propagation velocities on the order of 10^6 m/s. The determined vertical leader propagation speeds are an order of magnitude greater than those reported as typical values for stepped leader velocities associated with initial return strokes. *INDEX TERMS:* 3324

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Atmospheric electricity; *KEYWORDS:* lightning, leader processes, VHF lightning, VLF lightning, leader velocity

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1. Introduction

[2] The Los Alamos Sferic Array (LASA) is an array of electric field change meters operated as an experimental system for ground support of satellite observations of lightning. We now have a four year data set of over 5 million multistation, differential time-of-arrival located events. As part of a study of leader radiation detected in this data set, we have identified a small number of leader events for which both LASA and the FORTE satellite observed intense radiation from individual leader steps. LASA was used to determine the two dimensional plan position of the lightning discharge. FORTE observed pairs of pulses (the first pulse is from the direct RF emissions and the second pulse is from the ground reflected RF propagation). The pulse separation is used to determine the source altitude. The FORTE records have multiple pulse pairs which provides enough information to determine the vertical propagation velocity of the leader. A future paper will report on statistically significant leader studies based on the LASA data set. After an introduction to previous leader observations, LASA, and FORTE, this paper describes two lightning discharges for which both LASA and FORTE observed intense leader radiation within 6 ms of the return stroke.

1.1. Lightning Leader Activity

[3] The transient electrical activity of thunderstorms generates electromagnetic radiation events known as atmospherics, or sferics. A typical return stroke produces radiation with peak energy at a frequency of ~ 10 kHz [Volland, 1995].

Radiation at these frequencies propagates through the Earth-ionosphere waveguide and can be observed at large distances (>2000 km) from the source. The large current return stroke usually produces the strongest electric field transient and other lower-amplitude features within the electric field change waveform can be attributed to aspects of the discharge process (e.g., channel tortuosity and branching [Willett *et al.*, 2000] or leader activity, as presented in this paper).

[4] A negative cloud to ground lightning flash is often composed of multiple strokes. The initial stroke is preceded by a stepped leader that propagates downward from within the cloud at speeds on the order of 10^5 m/s. When the attachment of the leader to ground occurs, a high current return stroke propagates back up the channel. Subsequent strokes in the same flash (generally within ~ 300 ms) usually have dart leaders or dart-stepped leaders that propagate down existing ionized channels at higher speeds on the order of 10^6 m/s and trigger a subsequent return stroke after ground attachment [Uman, 1987].

[5] The velocity of a stepped leader is a significant parameter of the electrical-breakdown process [Gallimberti, 1979]. The leader propagation velocity is indicative of the spatial extent of the high electric field region within the cloud. Brook [1992b] suggested that the velocity of the leader propagation may be a direct proxy for the precipitation mix within the cloud, because ice crystals have a higher corona threshold. Therefore stronger fields over larger spatial regions can develop before the corona would alleviate the fields. The existence of large regions of strong fields would tend to produce faster leaders.

[6] A brief review of previous lightning leader studies follows. The reported velocities are highlighted in order to compare with the greater vertical velocities reported in the

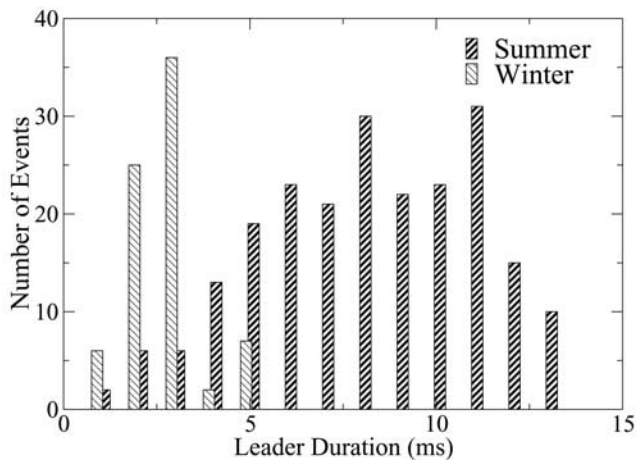


Figure 1. A histogram of leader durations based on data from Albany, NY, winter storms (1986–1988) and Kennedy Space Center, FL, summer storms (1991) (Krehbiel and Brook, private communication, 2001).

present paper. *Schonland et al.* [1938] reported electric field observations of two types of leader activity: α and β . The β leaders had initially large amplitude electric field changes that coincided with bright optical emissions from the leader. *Beasley et al.* [1982] identified the initial large-amplitude electric field change of β leader activity as being composed of “characteristic pulses,” which were attributed to a transition between preliminary discharges and stepped leaders [*Beasley et al.*, 1982].

[7] *Proctor et al.* [1988] provided a review of 13 studies reporting stepped leader propagation velocity. The range of velocities measured via photography, electric field change, 2-D interferometry, photoelectric, and hyperbolic radio (VHF time of arrival) studies was reported to be 2×10^4 to 7×10^6 m/s. The mean velocity of 66 events was 1.57×10^5 m/s. One “unusual lightning flash” described by *Uman et al.* [1978] was composed of three return strokes that “had unusually large peak currents and a stepped leader of relatively short duration,” with a velocity of 2×10^6 m/s. *Brook* [1992a] presented two electric field waveforms with intense leader radiation preceding an initial return stroke by <4 ms over winter thunderstorms. The work by Brook is difficult to access, so is described in more detail in the next paragraph. *Ogawa* [1995] presented four electric field waveforms with intense lightning leader features within several milliseconds, similar to those presented in this paper.

[8] *Brook* [1992a, 1992b] reports on fast/intense leader activity within 4 ms of the initial return stroke based on electric field change observations. The winter thunderstorm measurements are from Albany, NY, thunderstorms between 1986 and 1988. Similar observations were obtained on summer storms during the CAPE program at Kennedy Space Center, FL, in 1991. The winter thunderstorms were found to be much more likely to produce short duration leaders, with a mean duration of 2.75 ms. The observed summer storm leader duration was 8 ms with some summer thunderstorm leader durations as short as 1–3 ms. Figure 1 shows a histogram of the leader duration for winter and

summer thunderstorms (Brook and Krehbiel, personal communication, 2001).

[9] This paper presents a new method for determination of the vertical stepped leader propagation velocity, focusing on two events illustrating intense leader activity which has previously been considered unusual in storms. While searching many events to find coincident FORTE/LASA observations of intense leader radiation, the larger database of leader events (not presented in this paper) initially indicates that intense leader events are not as uncommon as has been indicated in the existing literature. A future paper will examine these issues in a statistically significant study.

1.2. Los Alamos Sferic Array

[10] The Los Alamos Sferic Array (LASA) was originally built for ground verification of lightning observations by the FORTE satellite. LASA has evolved into a tool for studying both FORTE and Global Positioning System (GPS) lightning observations, as well as a stand alone tool for studying lightning. LASA is an array of LF/VLF electric field change meters that utilizes GPS receivers to provide absolute event time tagging with an accuracy of better than 2 s. Using differential time of arrival methods for the event times at multiple stations, lightning events are geolocated. The records discussed in this paper are 8 ms in duration and have been collected by a threshold triggering mechanism that includes 2 ms of pretrigger data. In this paper, the trigger for described events was the leader radiation rather than the return stroke. The duration of the leader was sufficiently short that both the leader and return stroke were captured within a single 8 ms LASA record at multiple stations.

[11] During operations of the sferic array from 1998 through the present, stations have been located in New Mexico, Texas, Nebraska, Colorado, and Florida. The events in this paper were primarily recorded by the Florida stations. *Smith et al.* [2002] describe the operation and instrumentation of LASA and characterize the accuracy of LASA geolocation by comparison with the National Lightning Detection Network. The array accuracy analysis determines an accuracy of approximately 1 km within an array of stations.

1.3. FORTE

[12] The FORTE satellite was launched in August 1997 with instrumentation capable of making both radio frequency (RF) [*Jacobson et al.*, 1999] and optical [*Light et al.*, 2001; *Suszcynsky et al.*, 2000] observations of lightning. The orbit altitude is approximately 820 km at an inclination of 70° , providing at most ~ 12 min coverage of any ground location. The FORTE RF instrumentation consists of two tunable receivers with 22 MHz bandwidth and one tunable 85 MHz bandwidth receiver. The FORTE radio systems and typical observations are described by *Jacobson et al.* [1999]. The FORTE optical package consists of a fast, non-imaging photometer and a slower CCD array. The photometer has 15 μ s sampling and a 80° field of view. The CCD, which provides lightning location to ~ 10 km spatial resolution, is queried every 2 ms, and the pixel location and pixel value exceeding a noise riding threshold is recorded.

[13] If the FORTE-source geometry is favorable, intra-cloud lightning events produce RF pairs (separated temporally by as much as 120 μ s) from the direct and ground-reflected propagation paths. Given a two dimen-

sional geolocation and knowledge of FORTE's location, the source height can be determined from the delay between the pulses, as described by *Jacobson et al.* [1999]. For the events presented in this paper, multiple height determinations are made in submillisecond time periods. A vertical velocity between each step is computed based on the height determined and the time delay between the onset of each pair. Possible sources of errors include the LASA two-dimensional geolocation (<2 km), and the determination of the FORTE RF peak separation. Empirically, the errors associated with an accurate peak determination and errors in the height determination method lead to a velocity uncertainty $<10\%$.

2. Data and Analysis

[14] The FORTE RF data are processed on the ground by applying spectral whitening (to remove anthropogenic noise, such as radio and television transmissions) and dechirping (to remove ionospheric propagation effects) as described by *Jacobson et al.* [1999]. For some events, intermittent, narrow-band anthropogenic noise sources (e.g., radars) are removed via notch filtering.

[15] We present two detailed examples of leader radiation observed by FORTE RF sensors and the LASA electric field change sensors. The onset of the return stroke is identifiable in both the FORTE and LASA records and is therefore used as a fiducial point. We calculate the vertical propagation velocity in two ways: the vertical propagation velocity between steps is calculated using multiple pulse pairs and their temporal separation. The overall vertical propagation velocity is calculated using the height determined for the first pulse pair and the time to the onset of the return stroke.

2.1. 11 July 2000, 16:20:39

[16] The 11 July 2000, 16:20:39.615019 UT event was recorded by four sferic array stations, two of which triggered on the leader radiation and two of which triggered on the return stroke. FORTE triggered twice during the 8 ms LASA record, collecting two 546 μ s records. The first FORTE data collection was during the most intense leader radiation observed by the sferic array, and the second FORTE collection was during the return stroke. Figure 2a shows an 8 ms Kennedy Space Center (KC) waveform overlaid with the two 546 μ s FORTE RF records. The time origin is based on the sferic array trigger point. The sferic array located the event at 26.94°N and -78.07°E , which is ~ 200 km east of the Florida coast, and a distance of 309 km from the sferic array station at Kennedy Space Center. Figure 2b presents an expanded view of the 546 μ s plot of FORTE power associated with the leader activity. Three pulse pairs are identified in the FORTE data record. Based on the delay between the direct and reflected pulses, the source heights are 5.3 km, 5.0 km, and 4.3 km as indicated. Based on the time delays of 166.4 μ s and 119.3 μ s between the pairs of pulses, vertical velocities of 1.7×10^6 m/s and 5.4×10^6 m/s are determined. For the 285.7 μ s duration across all three pulse pairs, the average vertical velocity is 3.2×10^6 m/s. Based on the 5.3 km source height for the first leader pulse, and the 3.534 ms delay between the first leader pulse and the onset of the return stroke, a vertical velocity of 1.5×10^6 m/s is determined, in reasonable agreement with the vertical veloc-

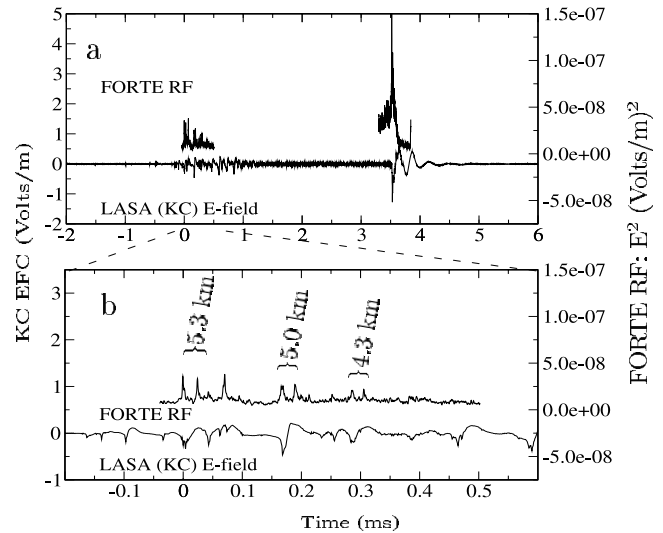


Figure 2. The 11 July 2000, 16:20:39.612521 event. (a) An overlay of the 8 ms sferic array (LF/VLF) waveform and two 546 μ s FORTE RF records. The FORTE collects were independently triggered. (b) An expanded view of the FORTE RF waveform and field change waveform with three pulse pairs indicated. The three pulse pairs are determined to be from sources at altitudes of 5.2 km, 5.0 km, and 4.3 km. The delays between the pulse pairs are 166.4 μ s and 119.3 μ s, which yield two values of vertical velocities: 1.7×10^6 m/s and 5.4×10^6 m/s or an average vertical velocity of 3×10^6 m/s.

ity calculated between the three leader pulses for which FORTE was able to determine heights.

2.2. 19 August 2000, 08:00:15

[17] A second example, from 19 August 2000, 08:00:15, is presented in Figure 3. This event was recorded by FORTE's 100 MHz bandwidth receiver with an 8 ms record length, while FORTE was operating with the optical systems as the event trigger source. Figure 3a presents the FORTE RF 8 ms power record (with a logarithmic mantissa) and the 8 ms electric field change record. Beginning at approximately -0.5 ms, several pulse pairs are apparent in the FORTE RF record. The pairs are temporally coincident with strong leader pulses in the LASA record. After the pulse pairs, the overall RF levels increases by almost a factor of 5. Figure 3b shows a 1 ms section of the FORTE RF record with pulse pairs associated with strong leader activity. The heights determined by the pair separations and the satellite geometry are labelled. The heights determined are 5.3 km, 4.9 km, 4.7 km, and 4.0 km, with delays between each pair set of 326.5 ms, 159.6 ms, and 317.4 ms. These values give vertical velocities of 1.4×10^6 m/s, 0.88×10^6 m/s, and 2.1×10^6 m/s for each successive step, and an overall vertical velocity of 1.6×10^6 m/s. The vertical velocity based on a leader at the height determined for the first VHF pulse pair (5.3 km) reaching ground at the time of the return stroke (4.83 ms) is 1.1×10^6 m/s.

3. Discussion

[18] We have presented ground LF/VLF and satellite VHF observations of unusual leader radiation. Based on

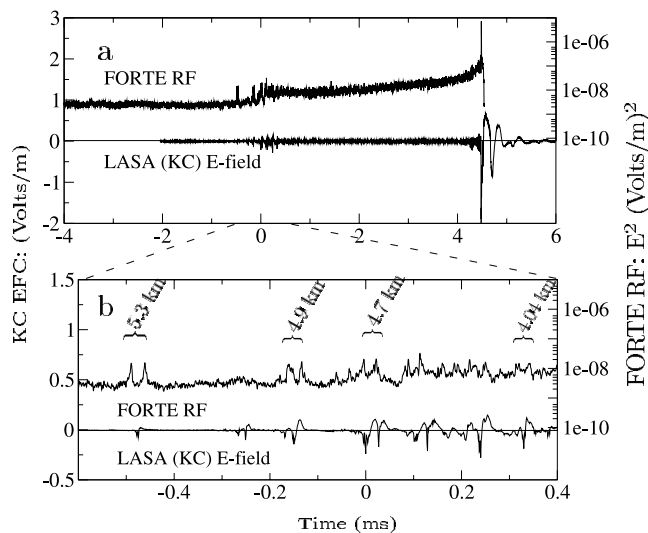


Figure 3. The 19 August 2000 event. (a) The 8 ms FORTE power vs time profile and the 8 ms Sferic Array VLF electric field waveform. (b) A 1 ms portion of the FORTE power versus time profile showing the pulse pairs used to determine leader heights. The altitudes determined are 5.3 km, 4.9 km, 4.7 km, and 4.04 km. The vertical velocities computed by these three steps are 1.4, 0.88, and 2.1×10^6 m/s. The overall vertical velocity for the 804 μ s duration of 4 pairs for which a height is determined is 1.6×10^6 m/s.

the LASA determined location of the event, we use the VHF observations to determine source altitudes of between 4.0 and 5.5 km within ~ 4 ms before an initial negative return stroke. Based on the altitude of multiple steps, vertical velocities of 10^6 m/s are determined. The multiple-step vertical velocity determination is consistent with the velocity required for the propagation of a leader from the initial height to the ground in the time between the initial leader and the return stroke. A total of four “intense” or “fast” leader/return stroke events observed by both FORTE and the sferic array have been identified. The average vertical velocity of all events is 2.1×10^6 m/s with a range of $0.88 - 5.4 \times 10^6$ m/s.

[19] One important issue regarding these observations is whether the observed leader is from an initial or subsequent return stroke (that is, a stepped leader or dart leader). Generally, initial return strokes generate the most intense electric field changes of a lightning flash [Rakov *et al.*, 1990]. The sferic array threshold triggering scheme causes stations to be most likely to trigger on and record initial return strokes. For the 19 August 2000 example presented, the FORTE photodiode record (not shown) is indicative of an initial negative return stroke [Light *et al.*, 2001], and the FORTE CCD location agrees with the sferic array determined location of 26.44°N and -79.11°E , east of the coast of Florida. FORTE observed the 19 August 2000 event presented in Figure 3 as the first stroke in a three stroke flash. The Kennedy Center sferic array electric field change record shows a relatively large amount of structure in the waveform within the initial return stroke pulse which is indicative of an initial return stroke. Based on evidence from both the FORTE and LASA observations, this event is

an initial negative return stroke. Of note, the FORTE RF observations presented in Figure 3 have the signature of a powerful, narrow negative attachment over seawater as described by Jacobson *et al.* [2000].

[20] Brook [1992a] proposed that intense/fast leader radiation were preferentially associated with winter thunderstorms. In contrast to this conclusion, the two examples presented here are both from summer thunderstorms. One FORTE/sferic array coincident observation of similar leader radiation occurred on 4 October 2000. All of the FORTE/LASA leader events identified to date occurred over seawater, but other sferic array observations of similarly intense leader activity associated with an initial return stroke have been located well within land masses (e.g., central New Mexico).

[21] This paper presents two examples of strong leader radiation recorded by the Los Alamos Sferic Array with coincident FORTE RF observations for which the FORTE source geometry and ionospheric conditions permitted the determination of leader altitudes. We are developing a database of leader radiation observed by the sferic array that will allow us to perform a statistically significant study of electric field changes associated with leader activity. The database will cover the four years of sferic array observations and should have approximately 300,000 leader events recorded at multiples stations. Once this leader database is completed, the occurrence rate of this intense leader radiation which is associated with fast leader propagation will be determined. FORTE overpasses of the sferic array coverage area are less 15 min long three times a day. During the overpasses, if there are lightning events, the FORTE source geometry and ionospheric conditions may not allow for resolvable pairs of pulses for the direct and ground reflection. For these reasons, the large majority of sferic array detected leader waveforms will not have coincident FORTE events with pulse pairs, so the height/velocity calculations presented in this paper will not be possible.

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